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Monsters in the Cosmic Sea: Black holes and Einstein's astrophysical legacy

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Monsters in the Cosmic Sea:

Black holes & Einstein's Astrophysical Legacy

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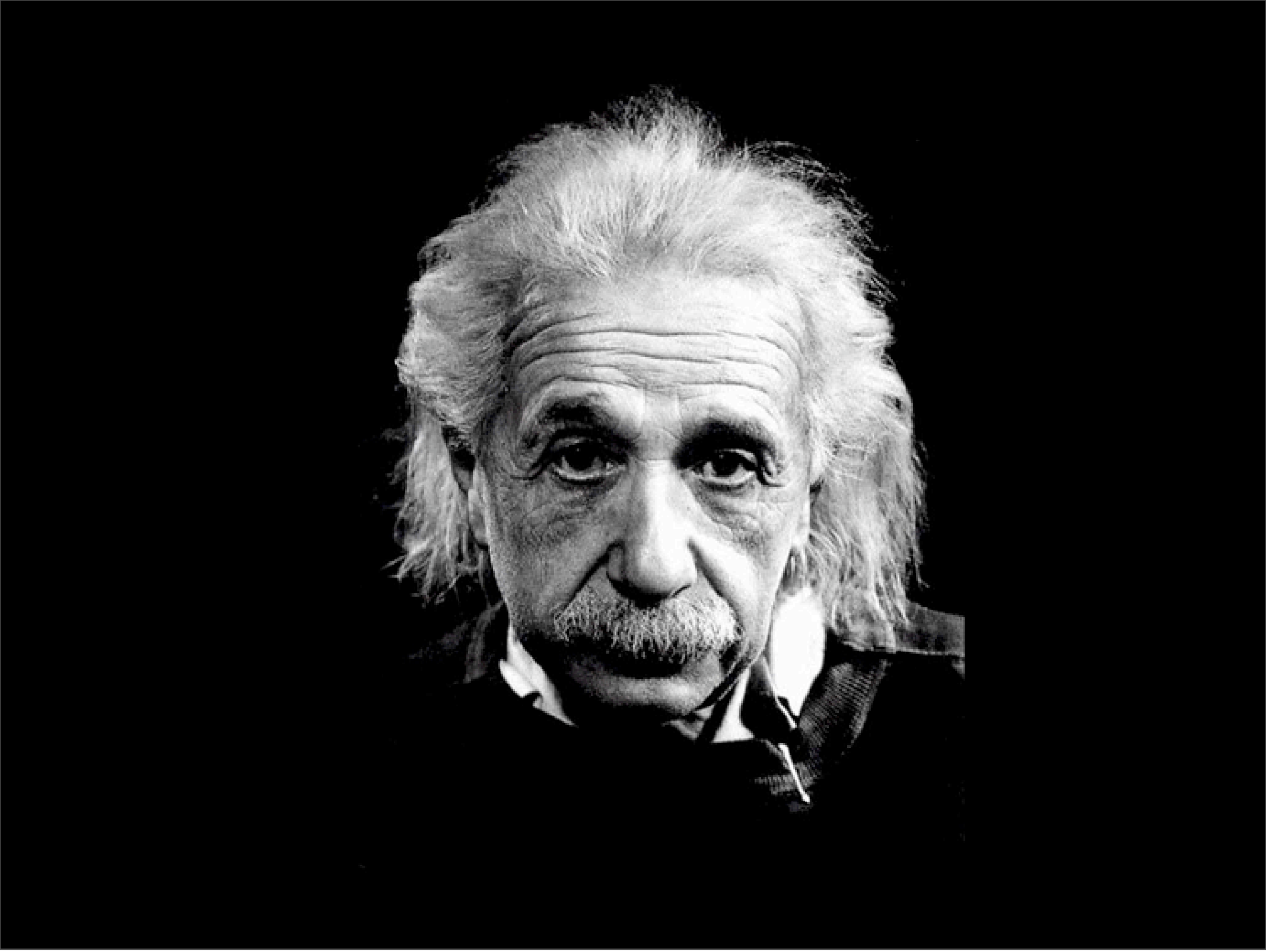
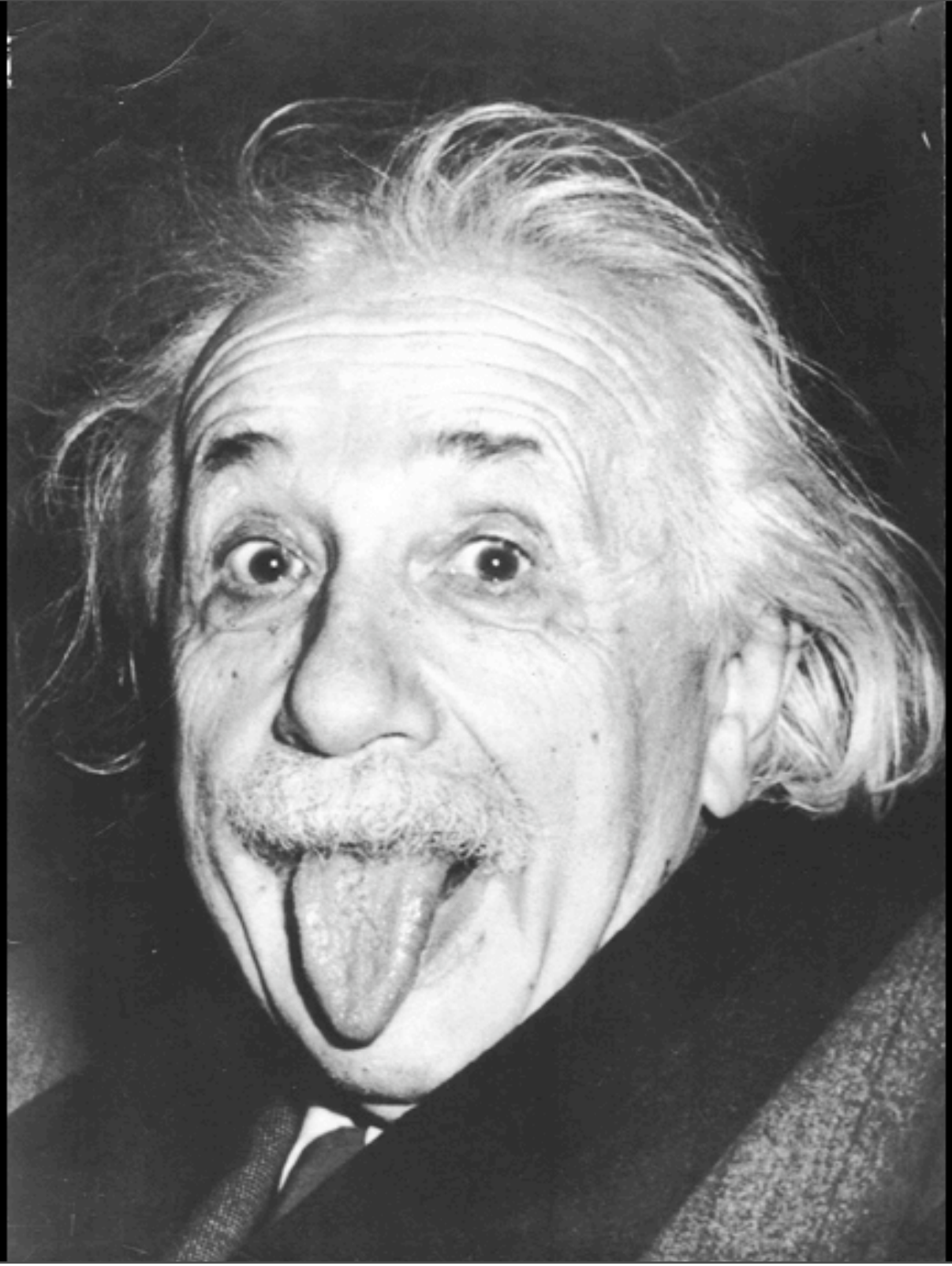
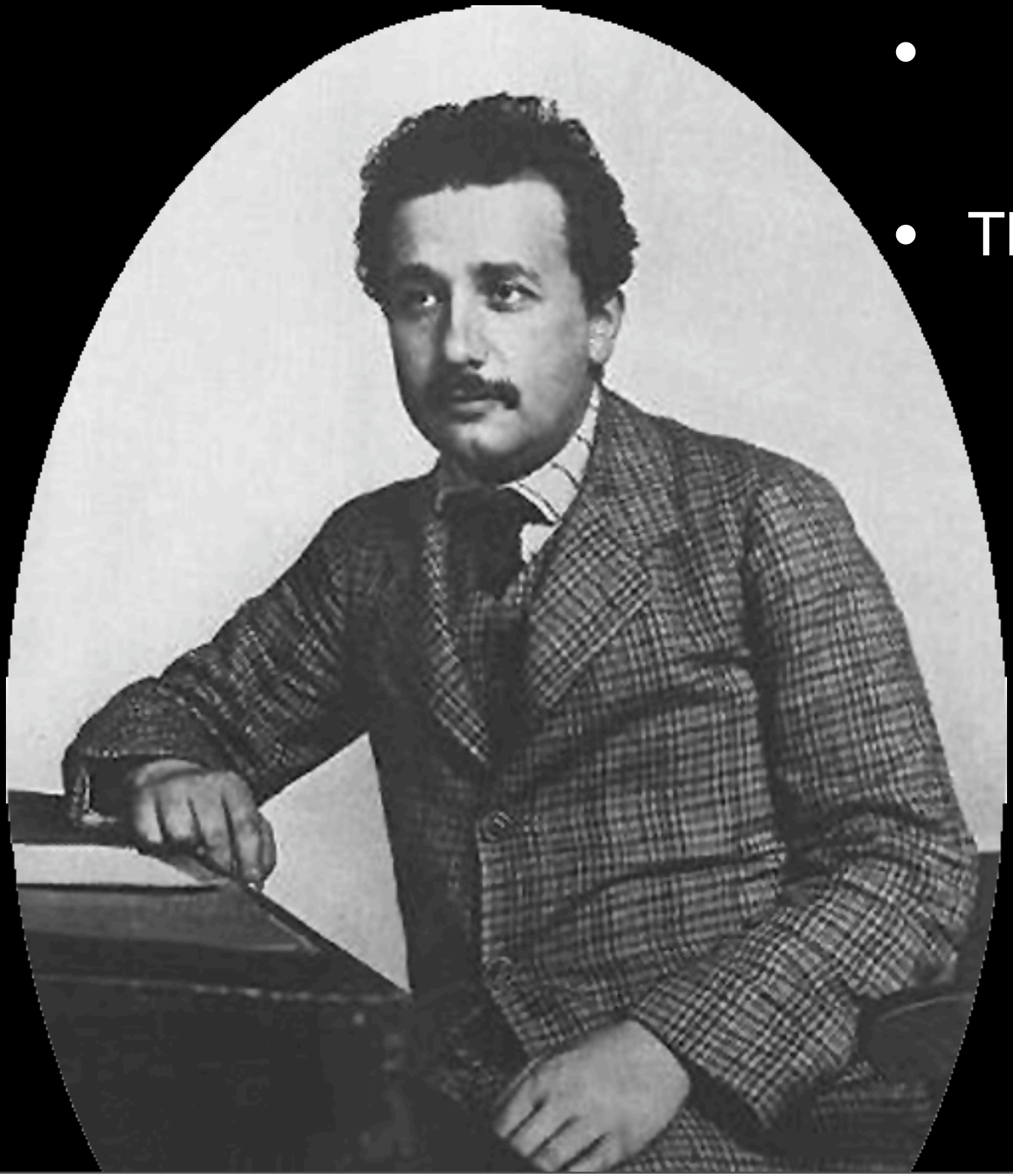
Storyline

- Einstein & the "Miracle Year"
- Einstein & modern gravity
- Black holes we have known
- Gravitational wave astronomy
- Listening to the songs of gravity




LEGO





- 1905: Patent clerk in Bern, Switzerland
- The "Miracle Year" was 3 papers:

Brownian motion

Photoelectric effect & the revival of the photon theory

Special relativity: ultimate speed limit

Gravity: Isaac Newton

- Isaac Newton (1642-1726)
  - Lucasian Professor at Cambridge
  - 1687 — Principia
  - 1704 — Optiks
- 🍎 Newtonian gravity was the first great physical law
  - Attractive force between masses, falls off with distance
  - Transmitted instantly
- Einstein knew this was incompatible with Special Relativity, and in 1915 introduced General Relativity

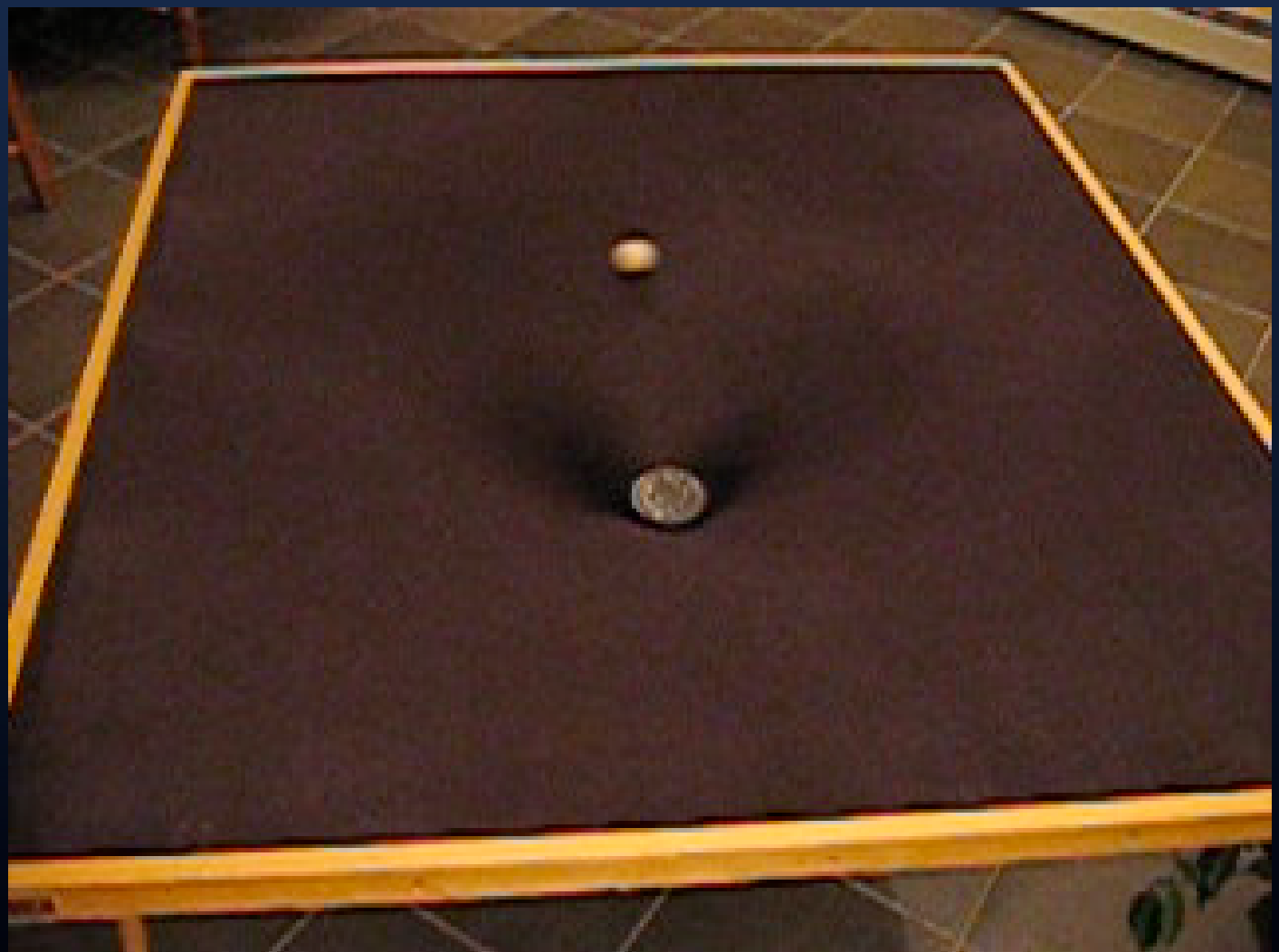
General Relativity

- Flat spacetime

General Relativity

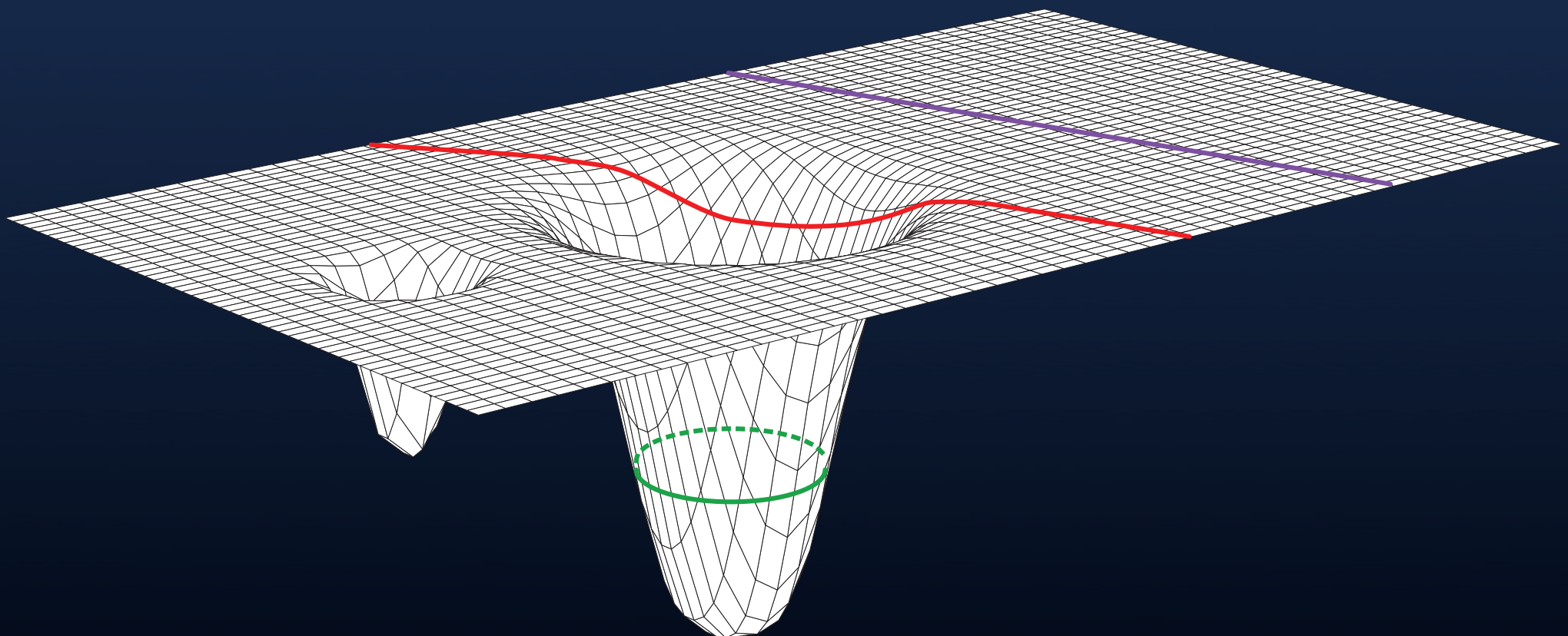
- Curved spacetime

General Relativity



- Spacetime gives ordinary orbits!

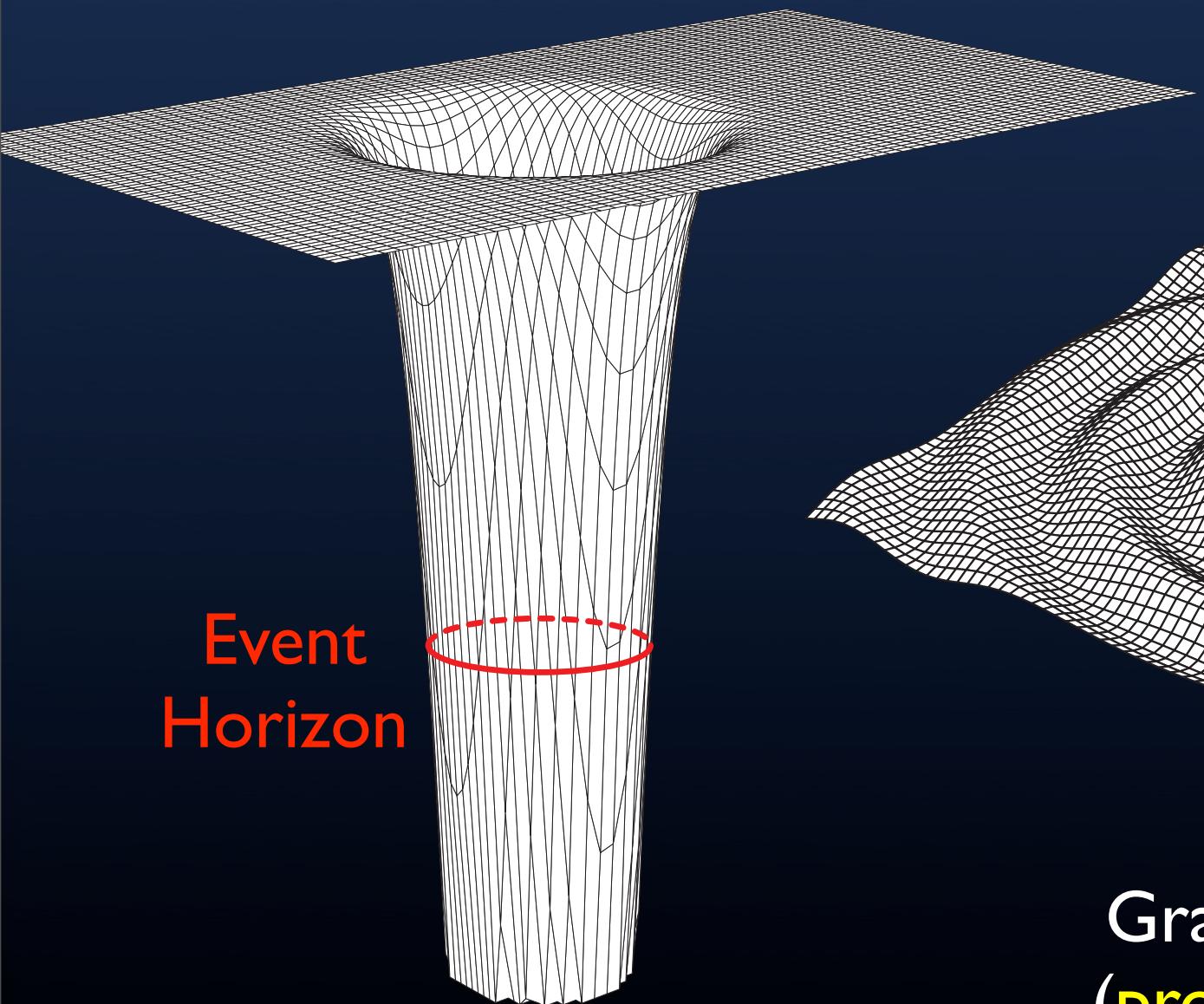
GR Summary



- Matter tells space how to curve
- Space tells matter how to move

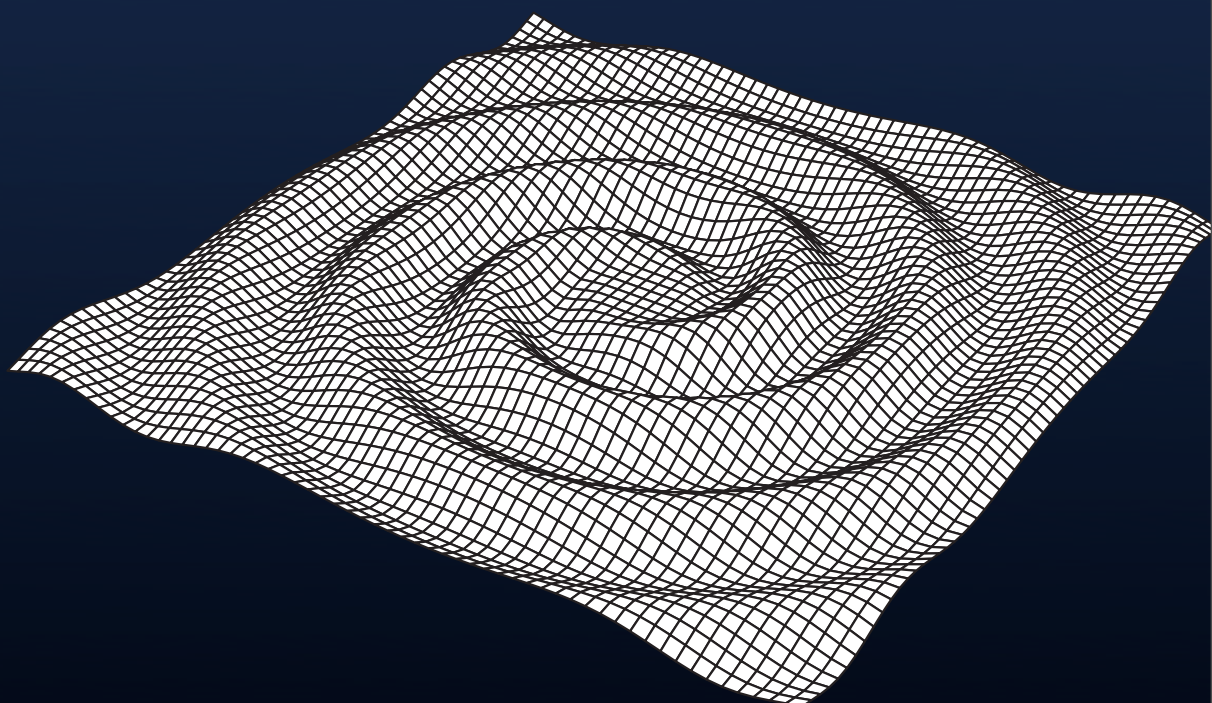

$G_{\phi\phi} = 8\pi T_{\phi\phi}$
MONTANA STATE UNIVERSITY
THEY BOUGHT IT

Consequences of GR



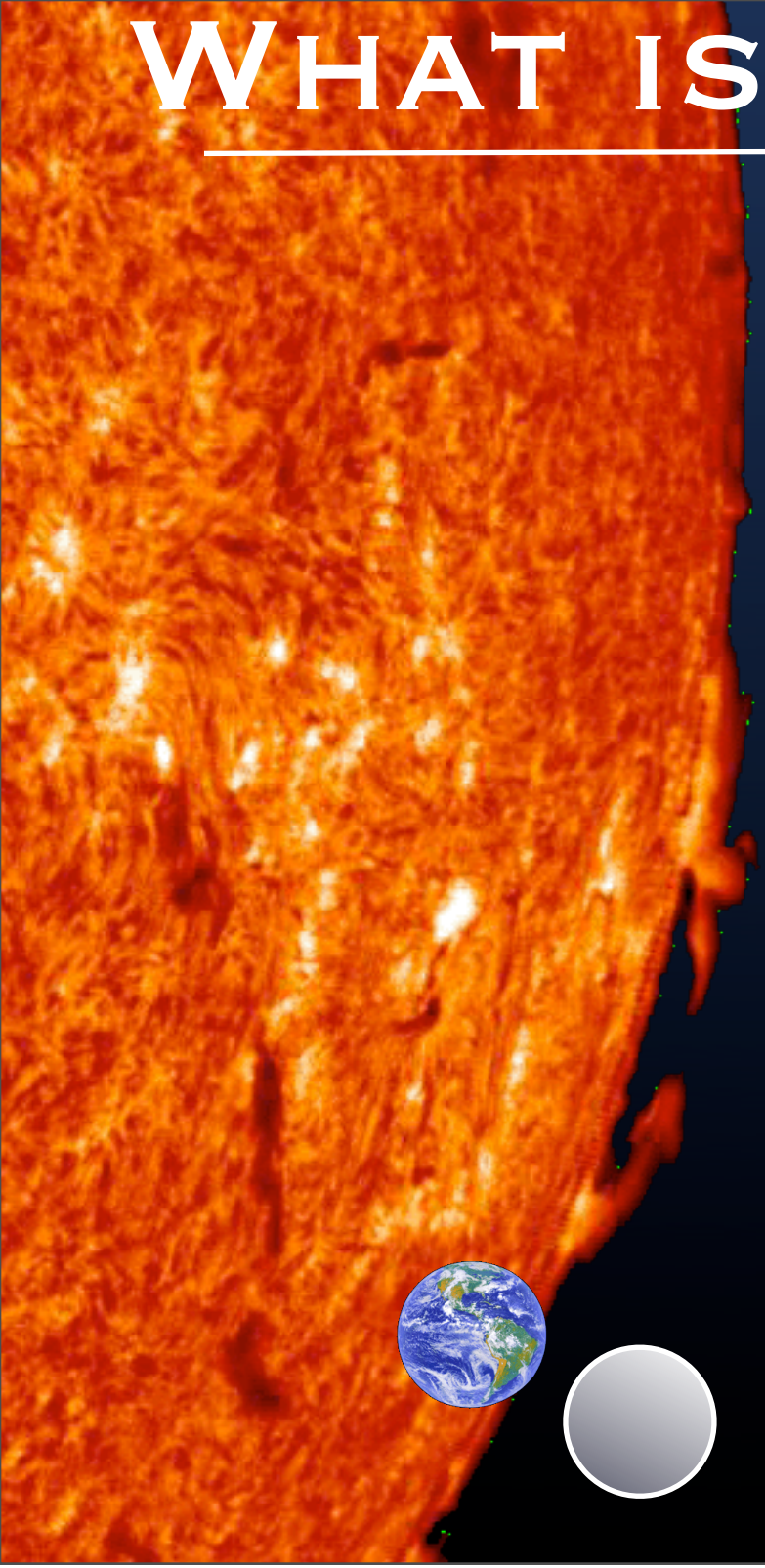
Event Horizon

Black holes
(infinite wells)



Gravitational waves
(propagating gravity)
(ripples in spacetime)

What is a black hole?



- Compact object, with HIGH ESCAPE VELOCITY
- Sun: radius = 1.4 million km
  - v = 618 km/s
- Earth: radius = 6400 km
  - v = 11 km/s
- white dwarf: radius = 6400 km
  - v = 6450 km/s
- black hole: radius = 3 km
  - v = c = 300,000 km/s

Not a new idea!

- Einstein did not invent black holes! Black holes are a natural consequence of gravity!
- Black holes were discovered in ***Newtonian gravity*** by Rev. John Mitchell in 1783 (!)

- What did Einstein add to the idea of black holes?
  - You cannot escape from a black hole
  - The speed of light is a maximum speed limit (special relativity)

Black hole observer's report

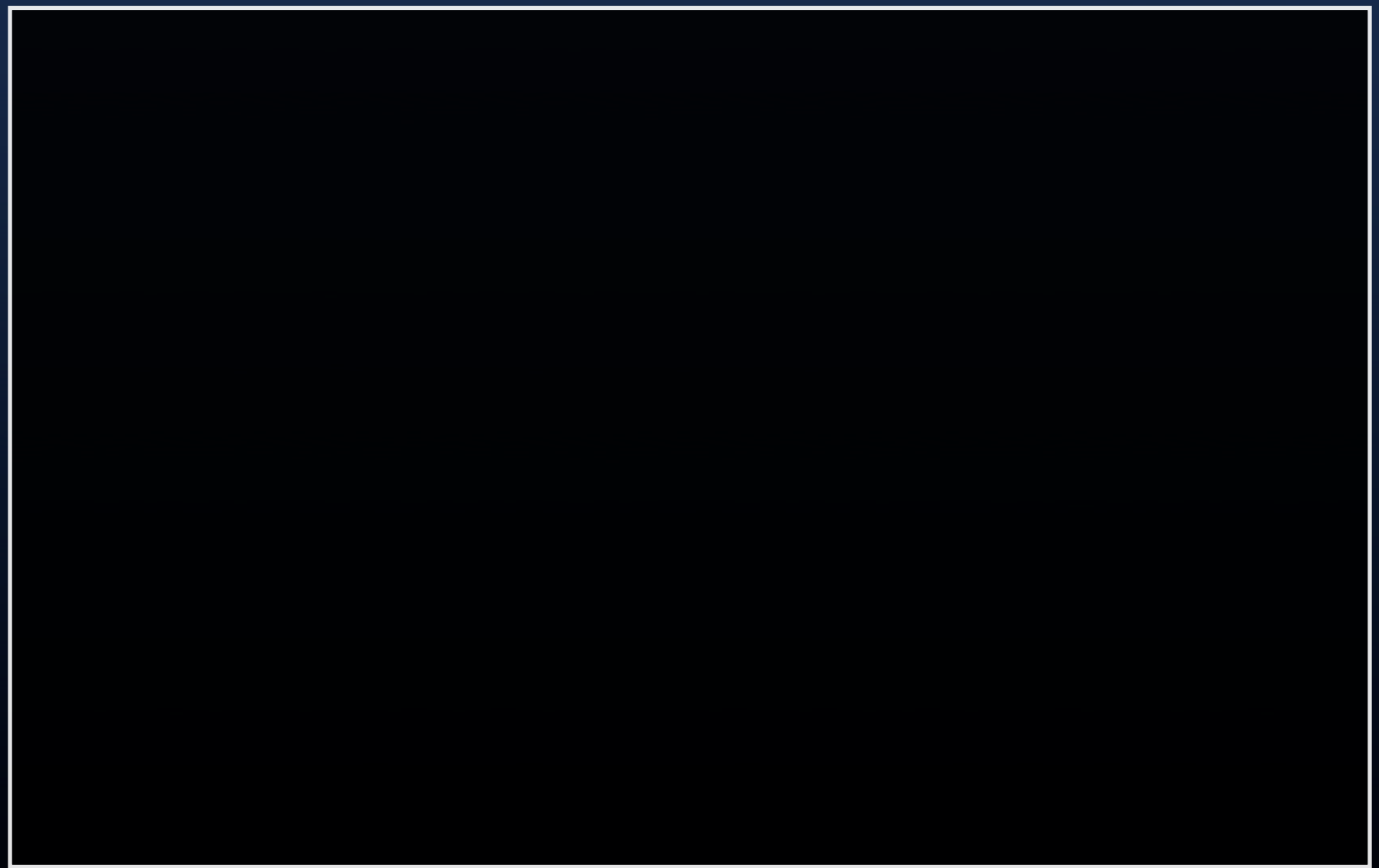
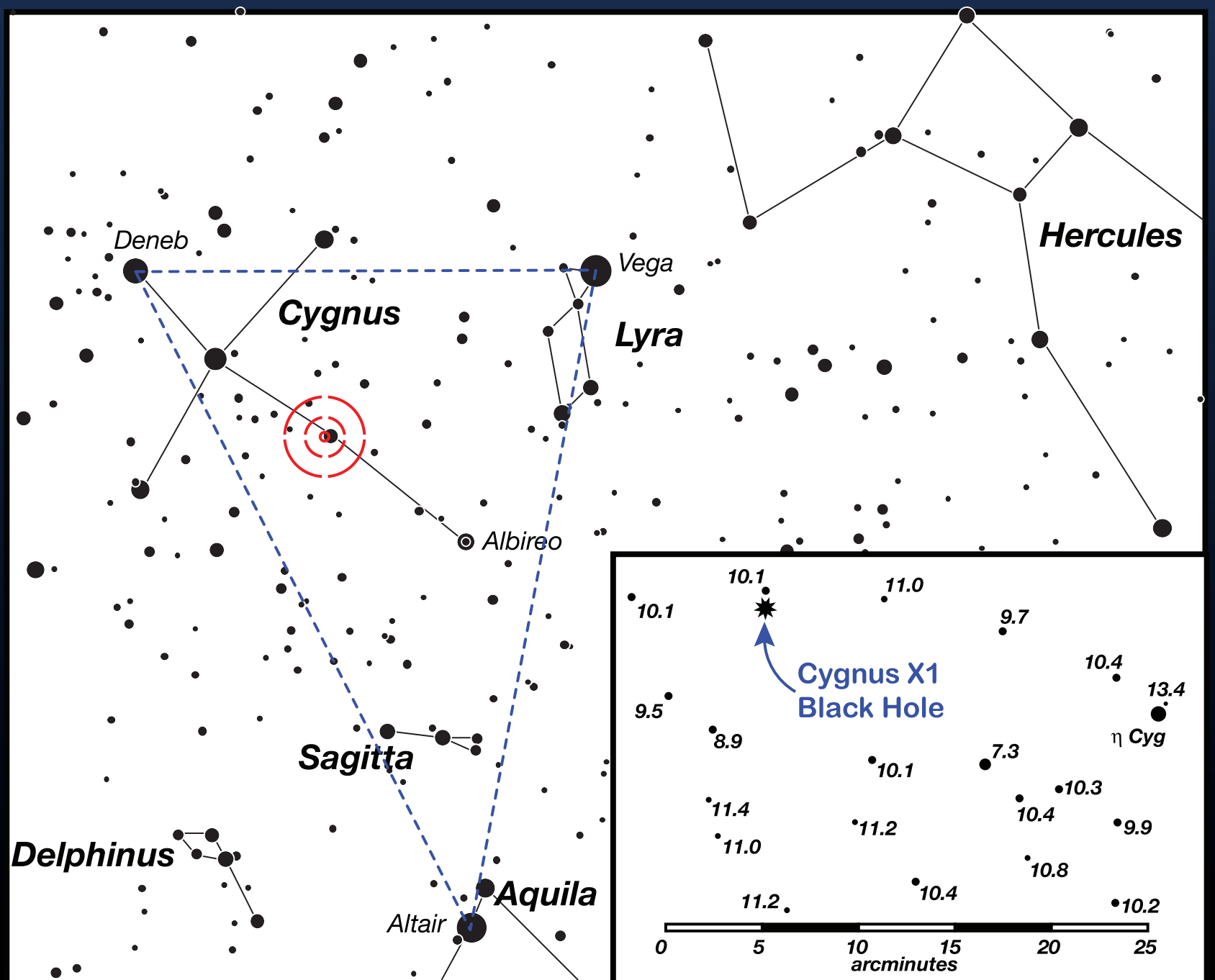
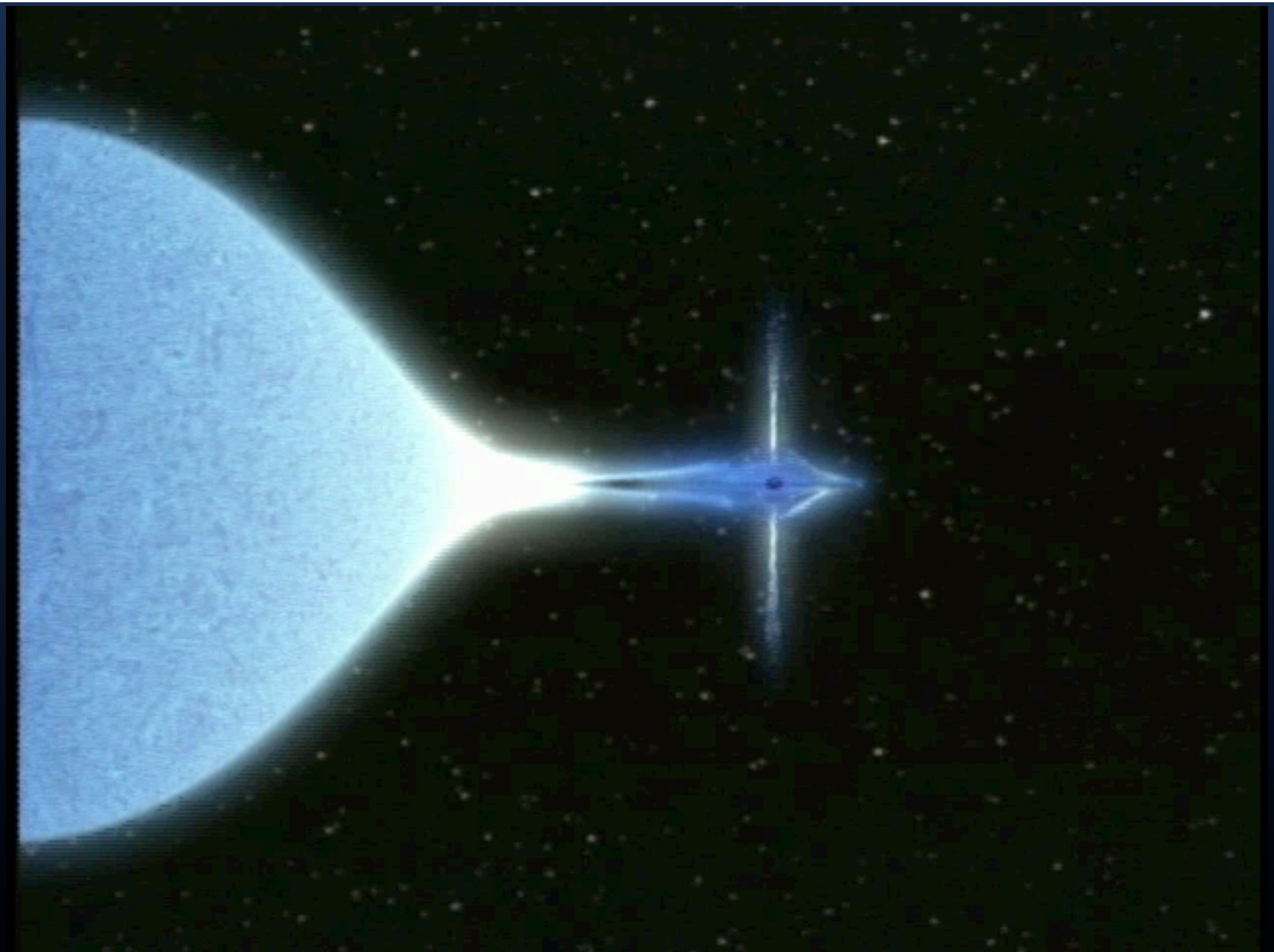


Image credit: M. Larson

Candidate: Cygnus X-1

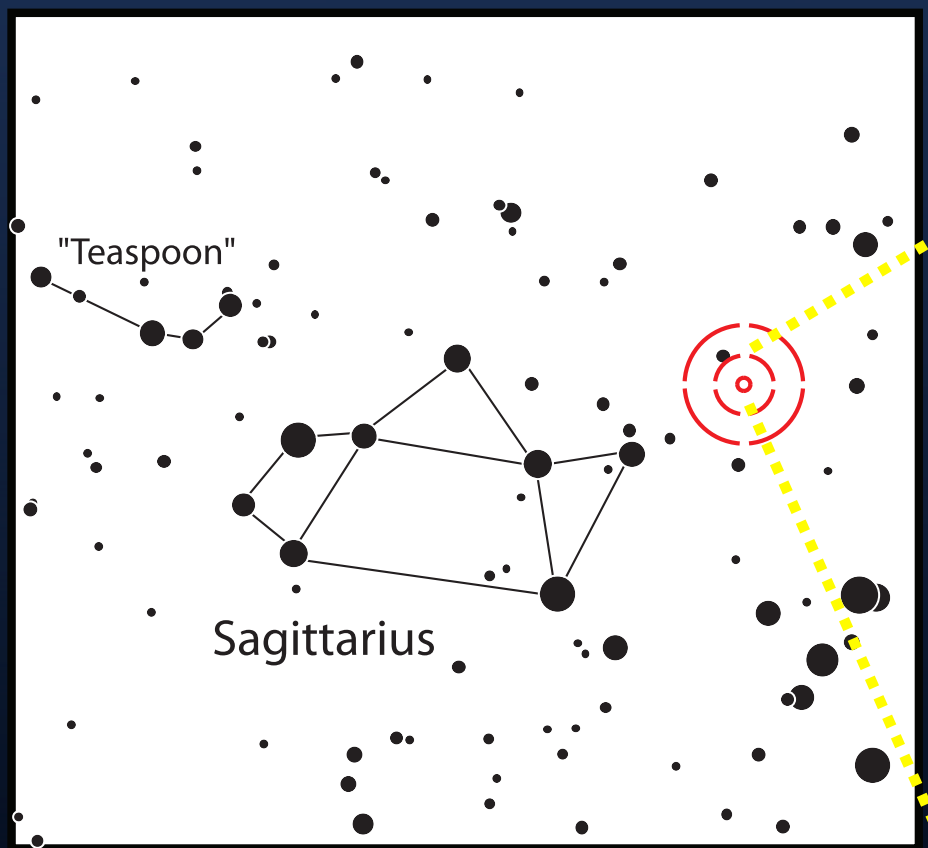


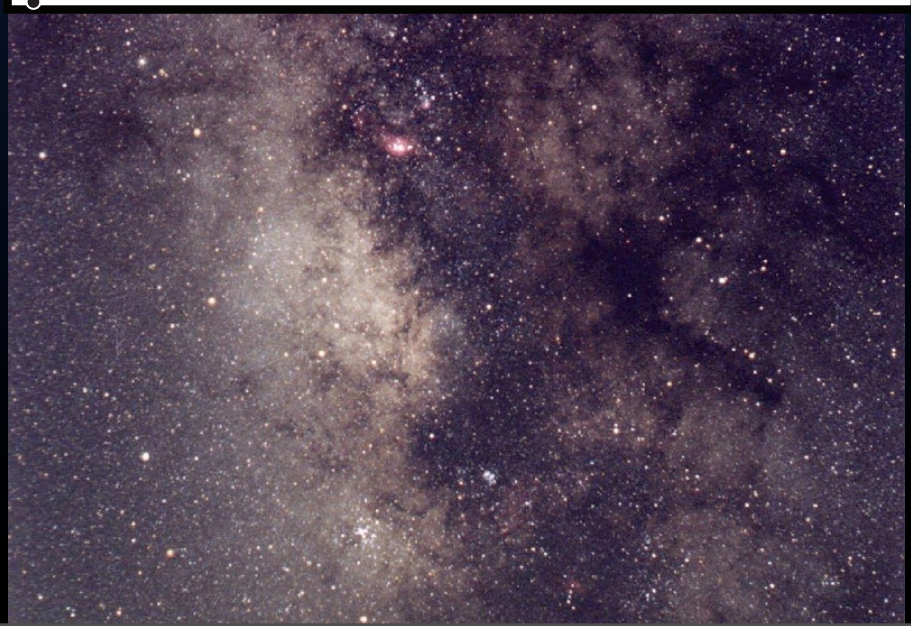
Candidate: Cygnus X-1

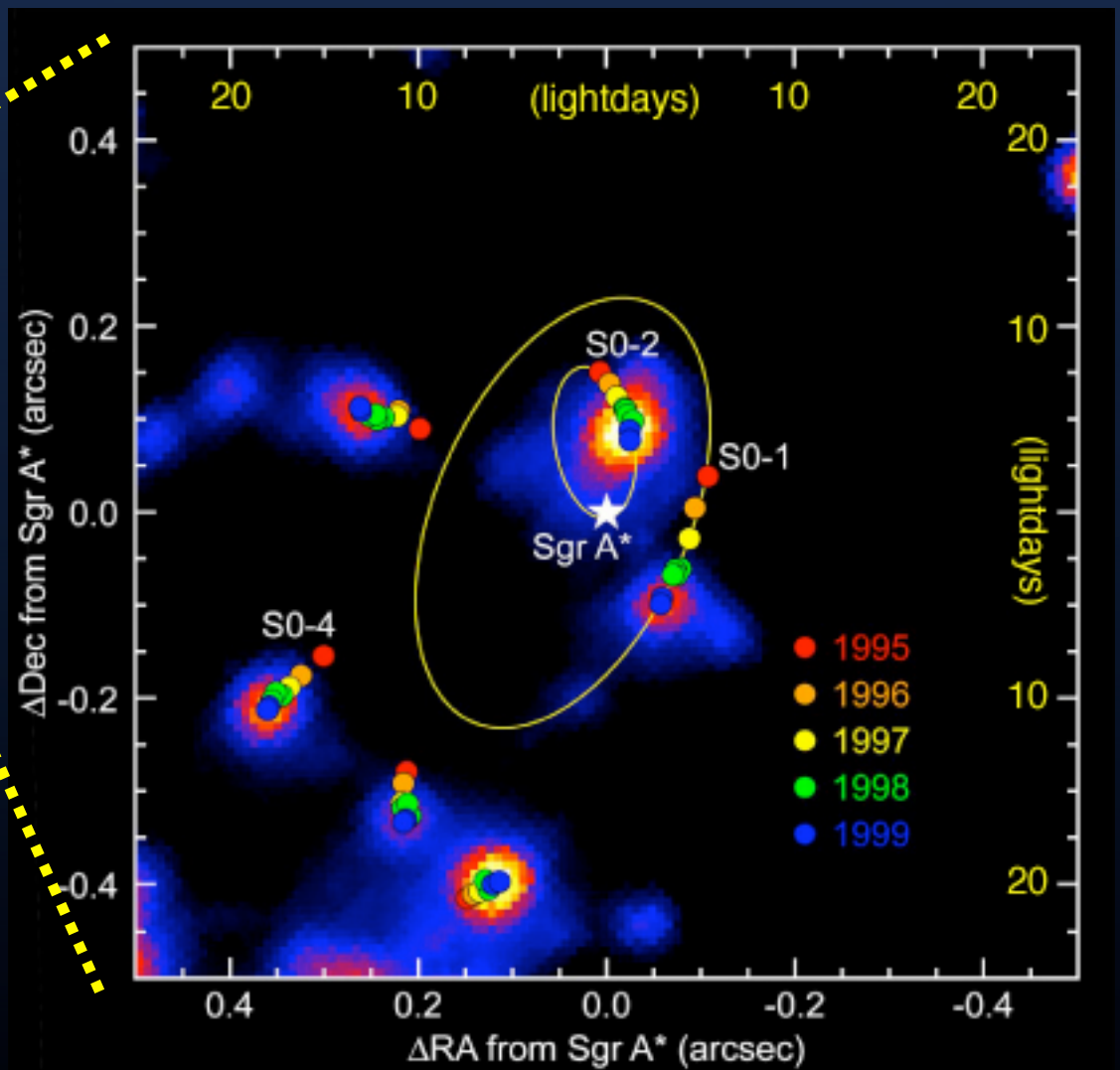


Invisible companion of a blue supergiant star is a suspected 10 solar mass black hole – the closest black hole to Earth!

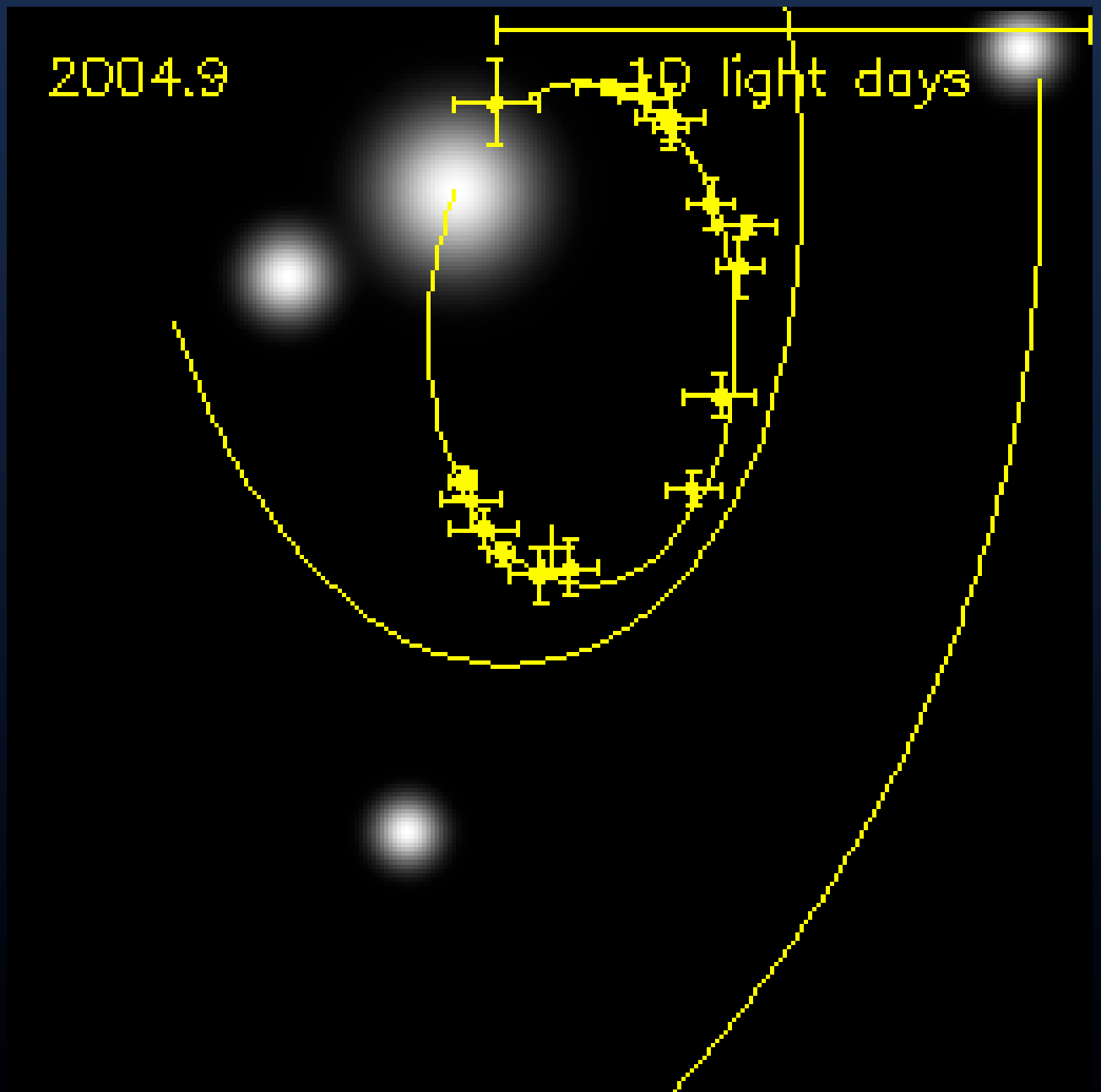
Center of the Milky Way





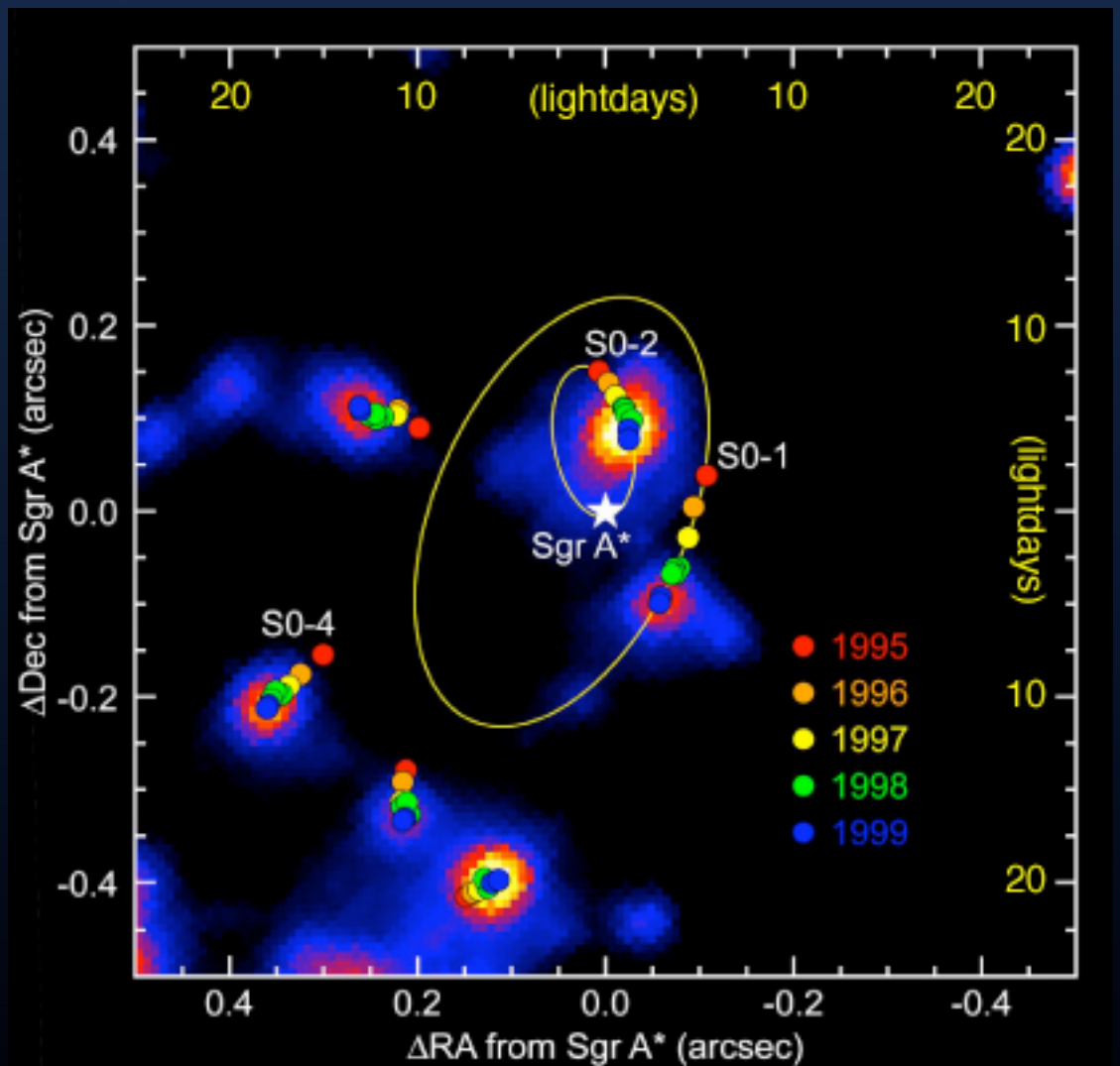


Stars in Motion



Explanation: 4 million solar Mass BH

- Why do we think this is a black hole?
- To explain the motion you need 35 billion stars per cubic lightyear
- If this were caused by stars and not a BH, there should be 90 million stars in this picture!

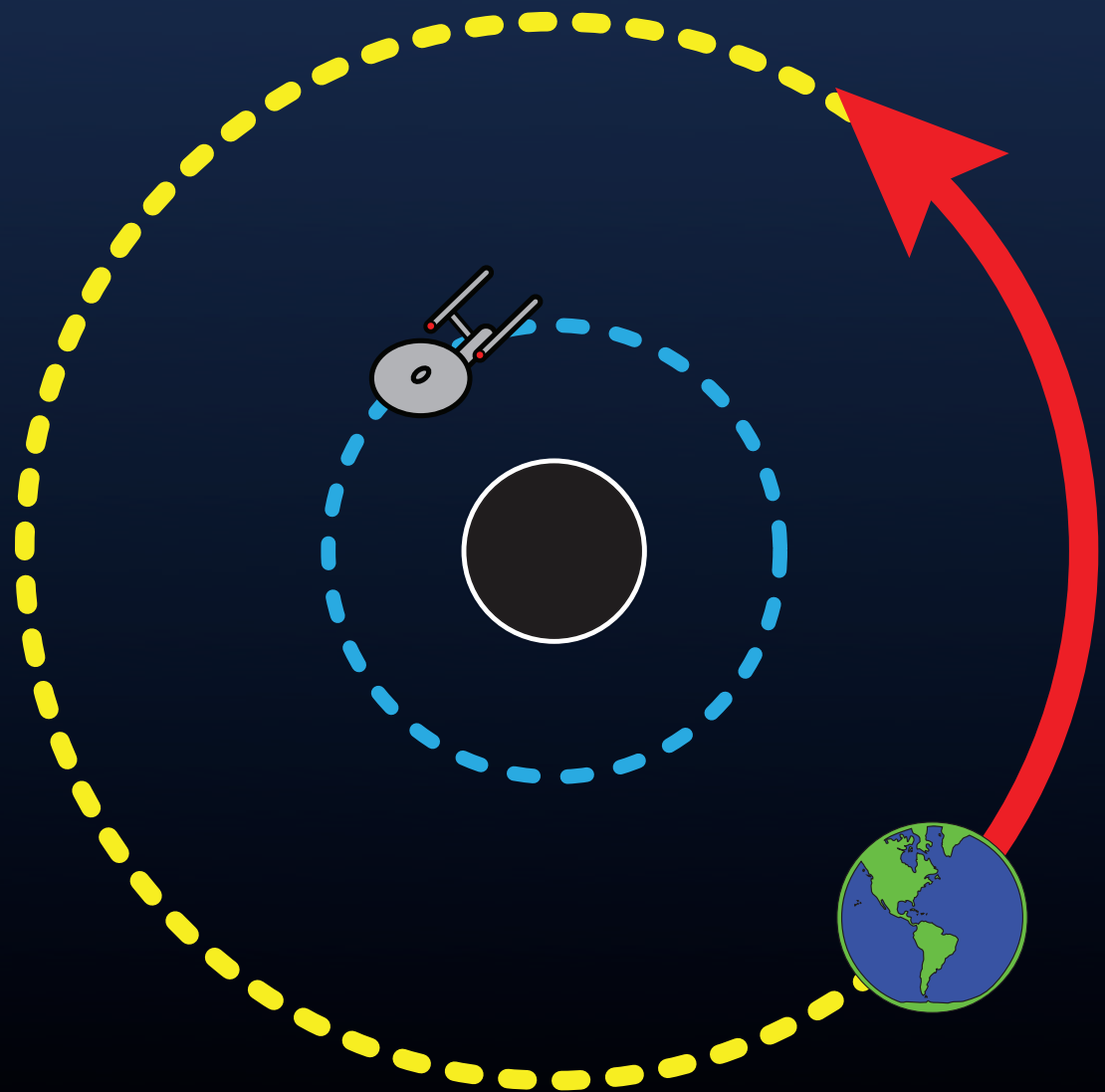


Exploring Black Holes

- Intrepid explorers (or infalling matter – stars, hydrogen gas, etc.) are needed to explore close to a black hole

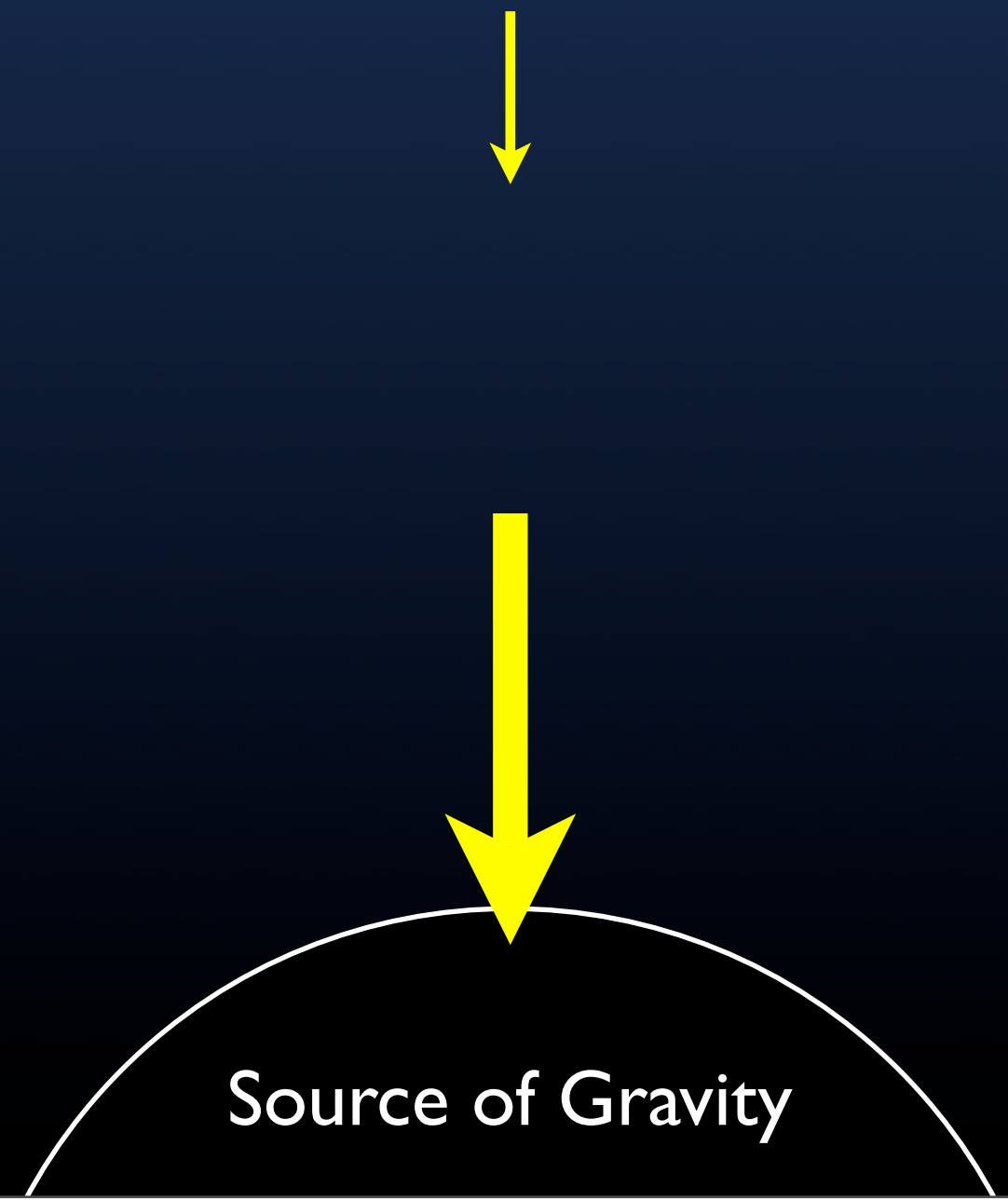
Near the Black Hole

- Far away, you can't tell its a black hole
- As you get closer, the black hole stretches space and time
- Starship clocks run slow near the black hole
- Your friends you left behind measure different distances than the crew



Tidal Forces

- As you approach a black hole, it pulls harder on the parts close to it -- tidal forces
- Eventually, tidal forces pull you apart
  - Spaghettification
- Destroy stars this way



Tidal Forces

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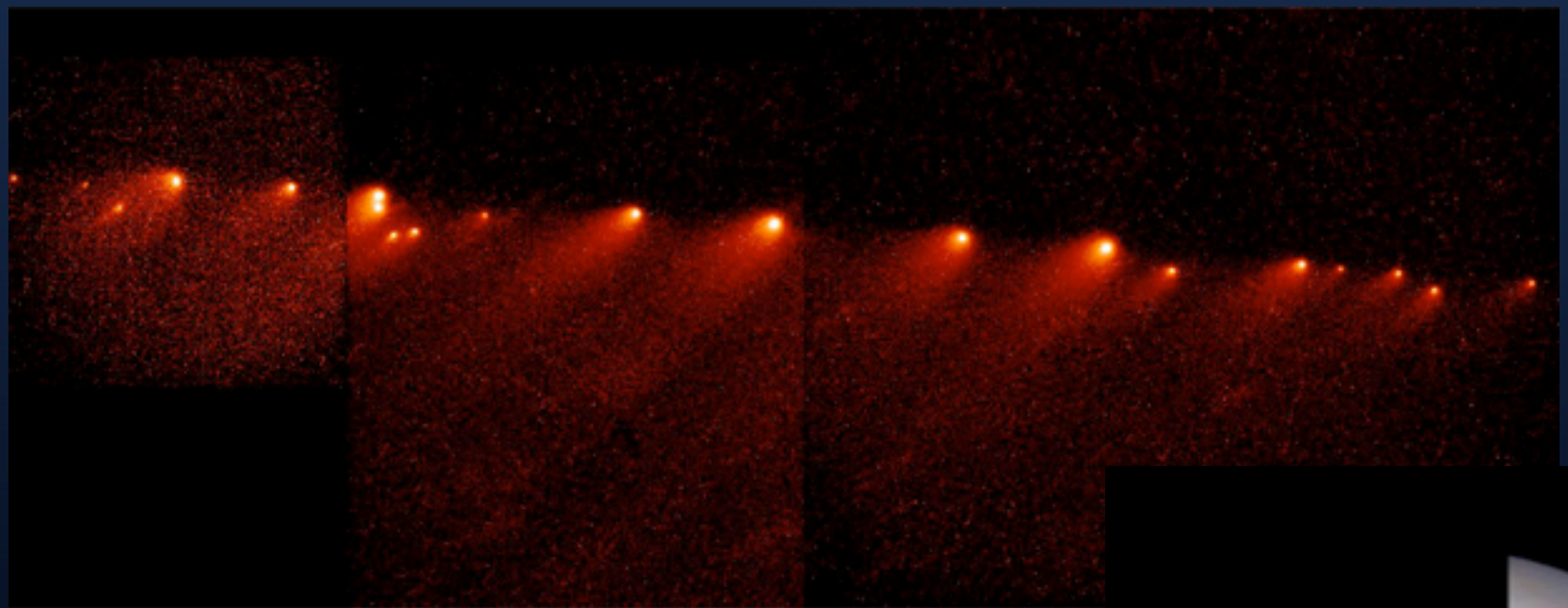
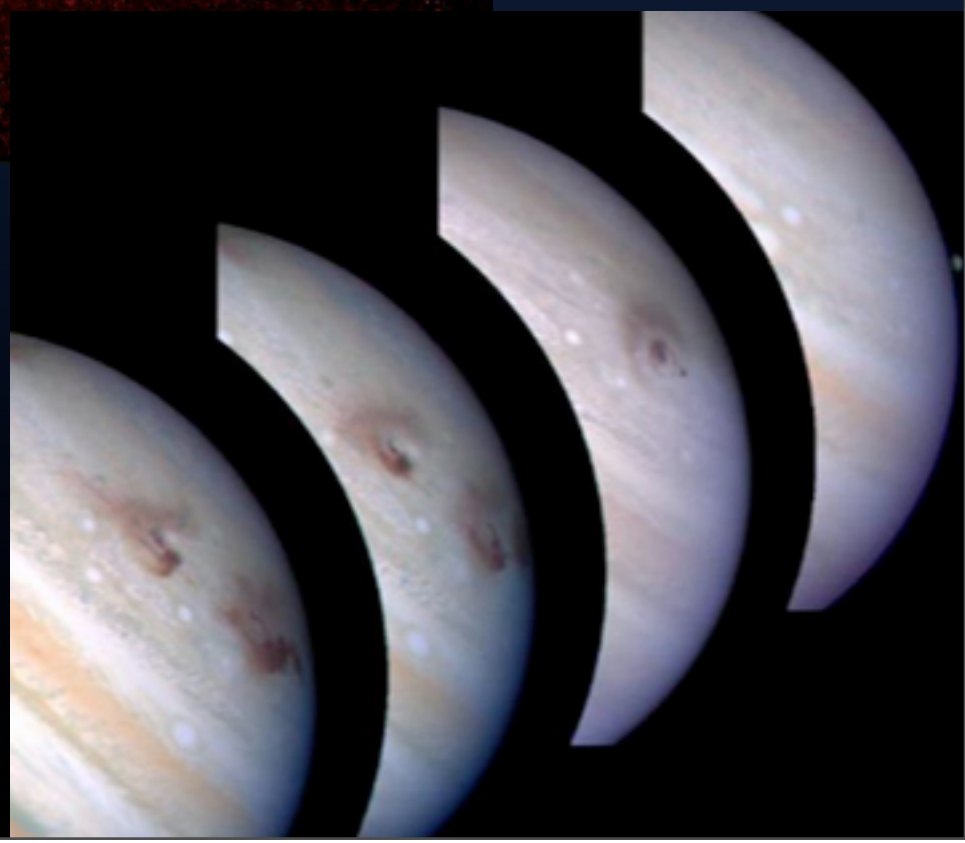
Black Holes Eating Stars

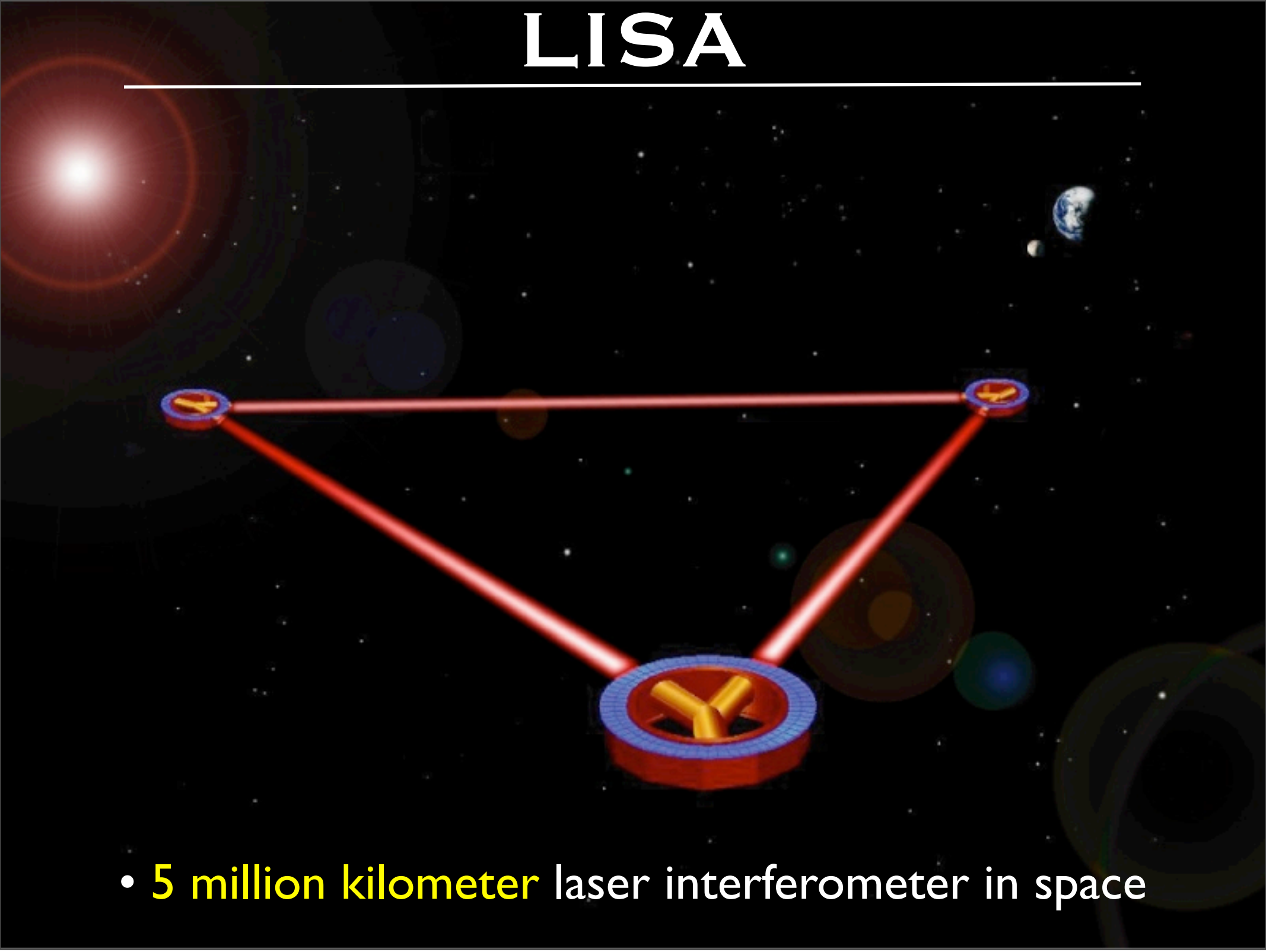
Tidal Forces are Not Unique to Black Holes



- 1992: Tidal forces rip apart Shoemaker-Levy 9
- 1994: Remnants of SL9 impact Jupiter

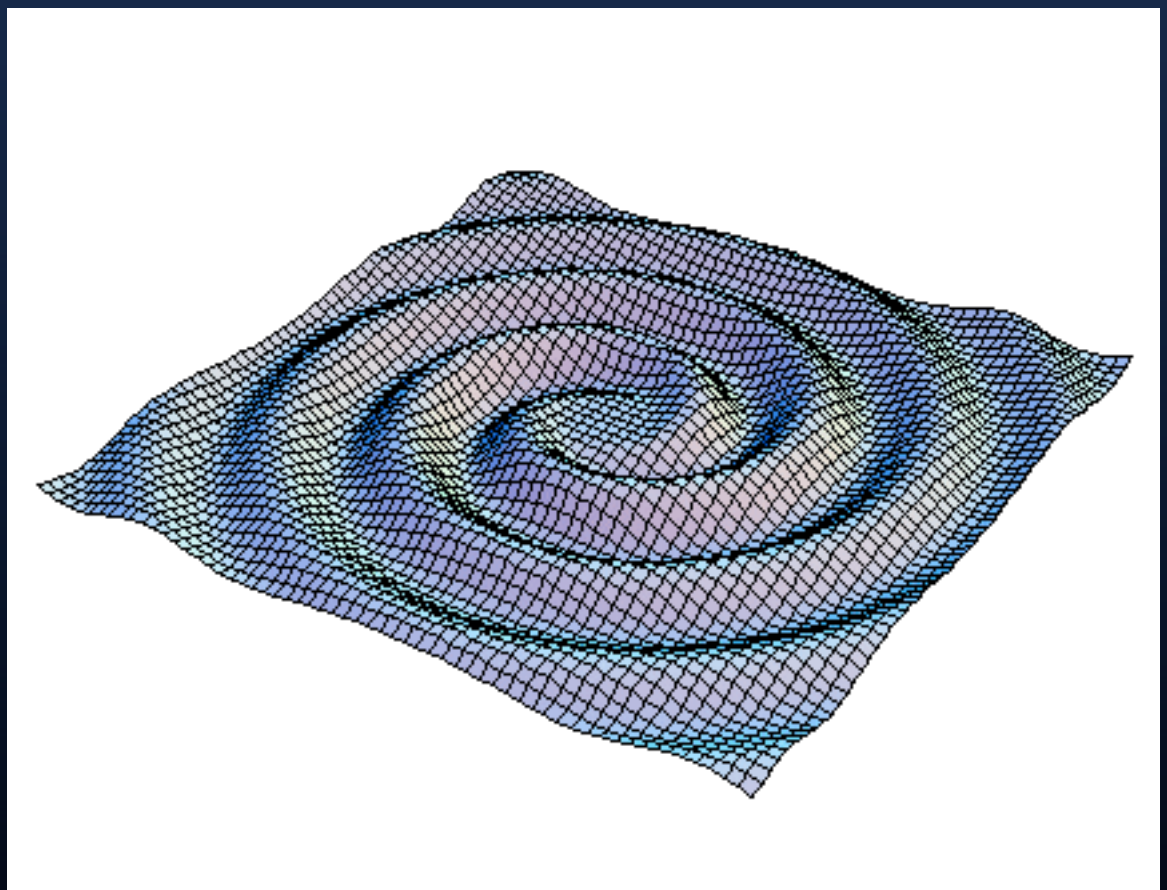


LISA



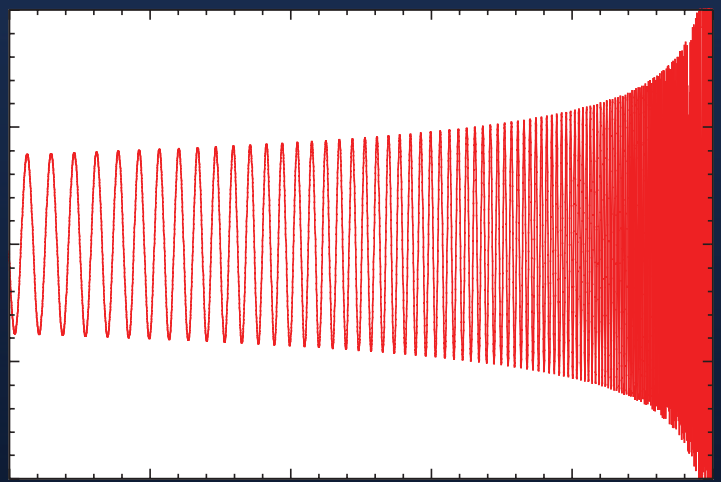
- 5 million kilometer laser interferometer in space

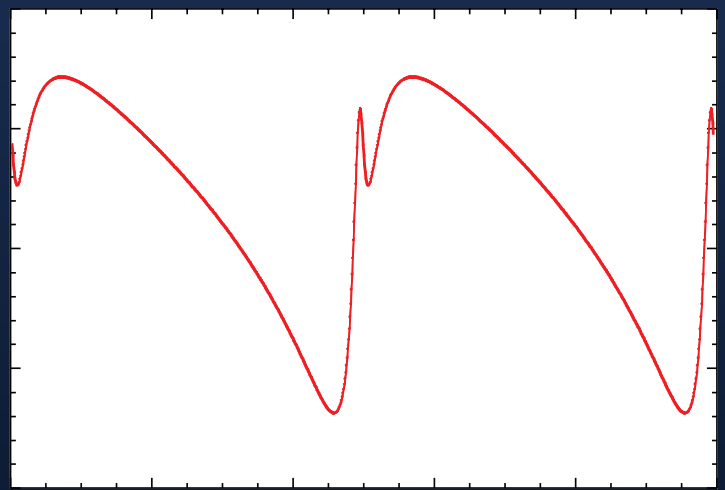
Binary Black Holes

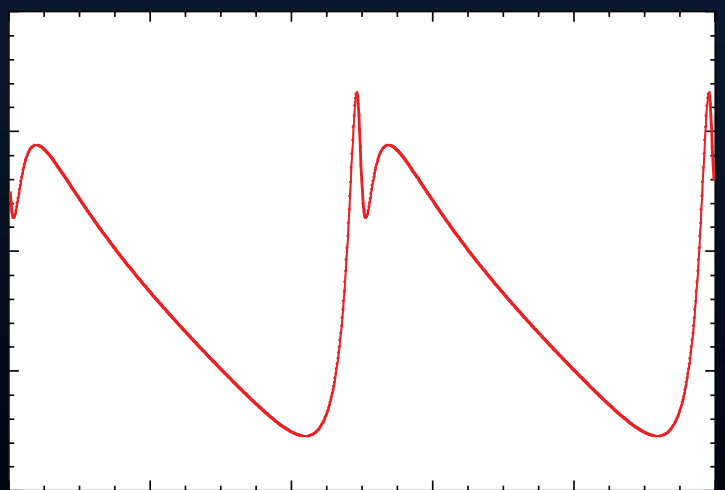


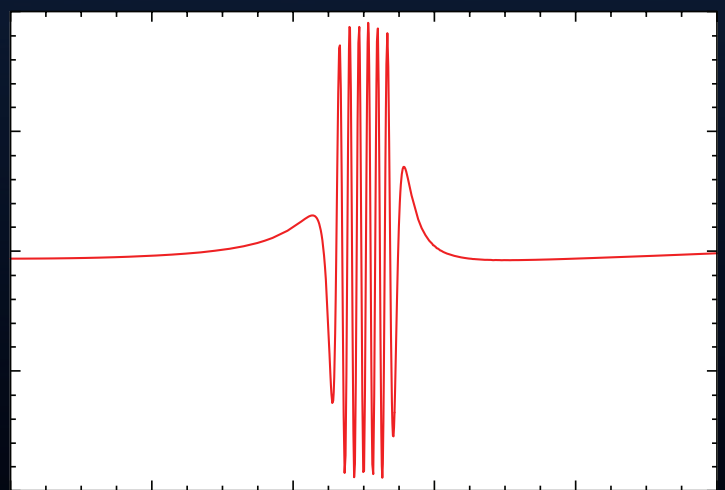
- Half of all stars we see in the sky are binaries
- If stars evolve into black holes, then binary star systems can evolve into binary black holes!

Waveform Zoology









- Gravitational waves encode astrophysical information!
- They aren't good for making pretty pictures! :-(

The Songs of Gravity

10 Msun BH + 10,000 Msun BH
circular orbits

10 Msun BH + 10,000 Msun BH
eccentric orbits

FOR MORE INFORMATION...

- ALBERT EINSTEIN
  - www.aip.org/history/einstein/
- LISA
  - lisa.nasa.gov

- BLACK HOLES AND TIME WARPS (Kip S. Thorne)

- EINSTEIN'S UNFINISHED SYMPHONY (Marcia Bartusiak)

Enjoy Observing!